Transverse Λ polarization and small-x physics

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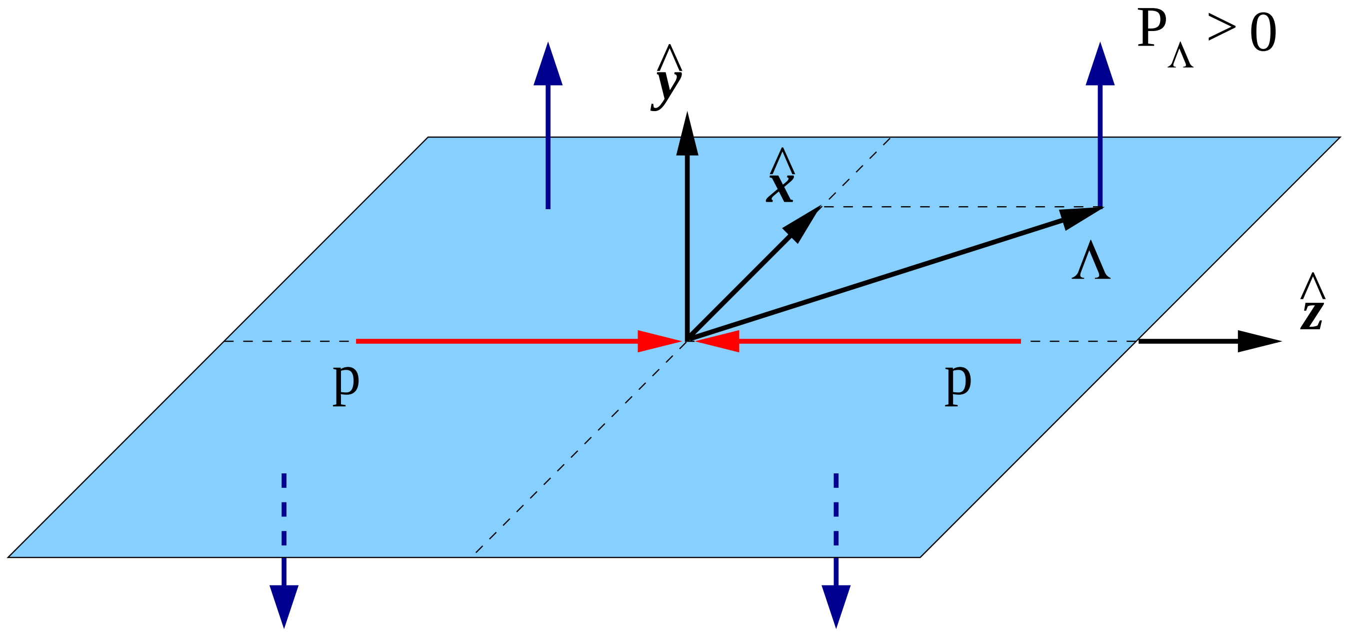
Outline

- Brief overview of transverse Λ polarization in $p + p \to \Lambda^\uparrow + X$: data & features
- Theoretical considerations: models and pQCD expectations
- Possible underlying mechanism in the intermediate to high $\boldsymbol{p}_T$ region:
  transverse momentum and spin dependence in the fragmentation process
- Analysis of $p + p(Be) \to \Lambda^\uparrow(\bar{\Lambda}^\uparrow) + X$
- Comments on high energy hadron collider data and the role of gluons
- $p + A \to \Lambda^\uparrow + X$ in the forward region as a probe of saturation physics

Transverse Λ polarization in unpolarized scattering

Large asymmetries have been observed in $p + p \to \Lambda^{\uparrow} + X$

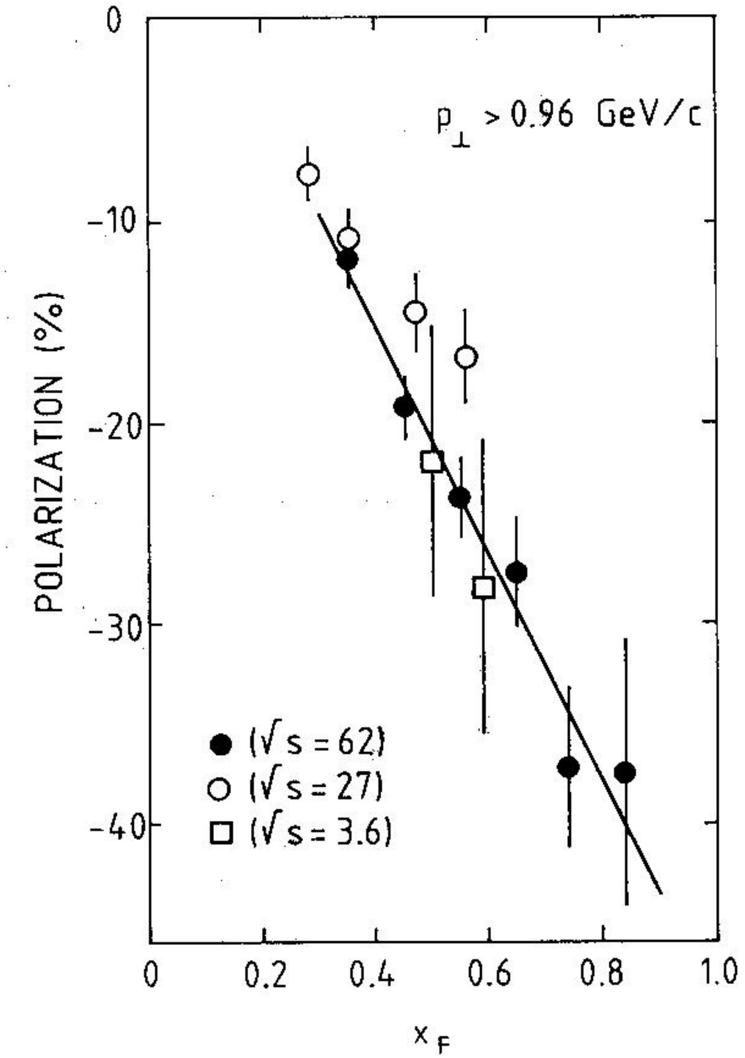
G. Bunce *et al.*, PRL 36 (1976) 1113



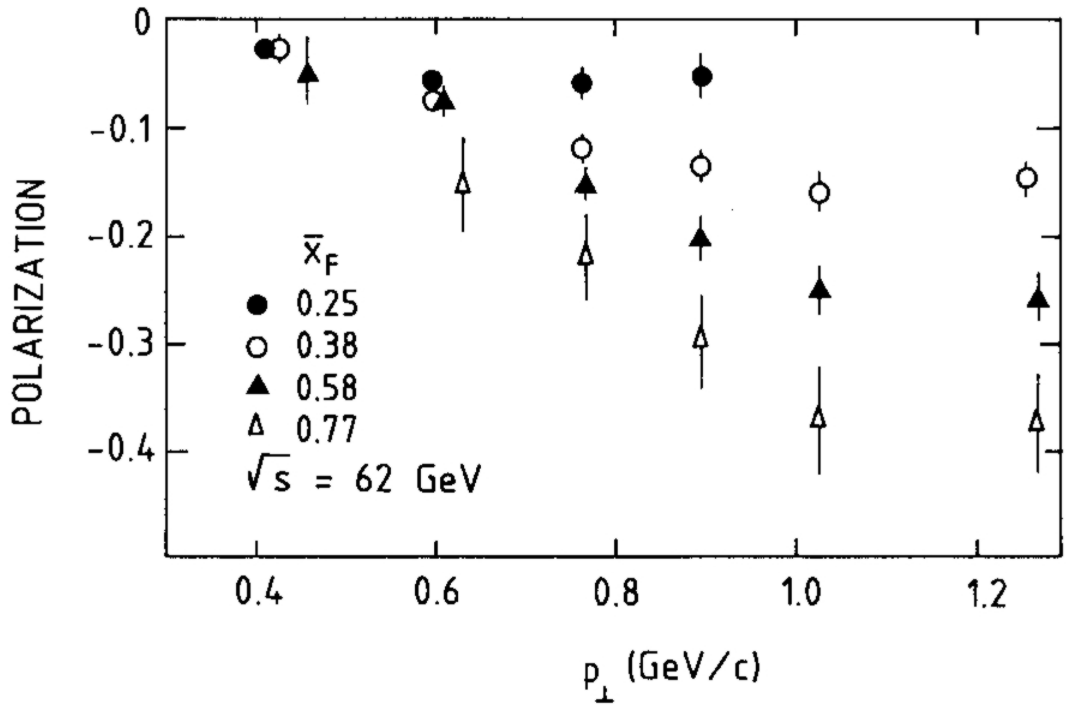
Blue arrows indicate the direction of positive transverse (w.r.t. production plane) polarization P_Λ, in the four quadrants

For symmetry reasons $P_\Lambda = 0$ at midrapidity

Generic $p\,p$ data - x_F and p_T dependence

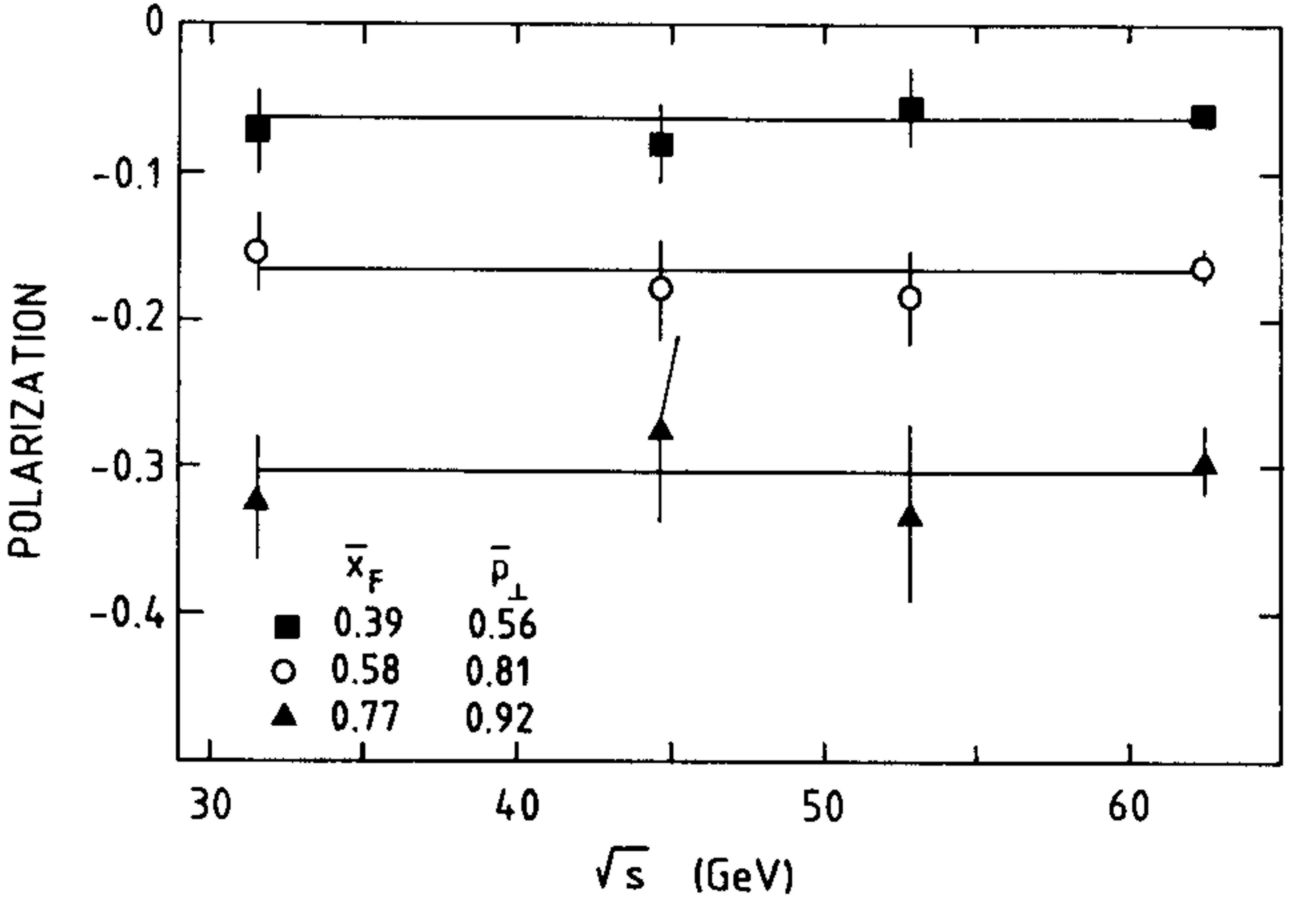


P_Λ turns out to be negative



For p_T above 1 GeV$/c$ P_Λ becomes flat (measured up to 4 GeV/c)

Generic pp data - $\sqrt{s}$ (in)dependence

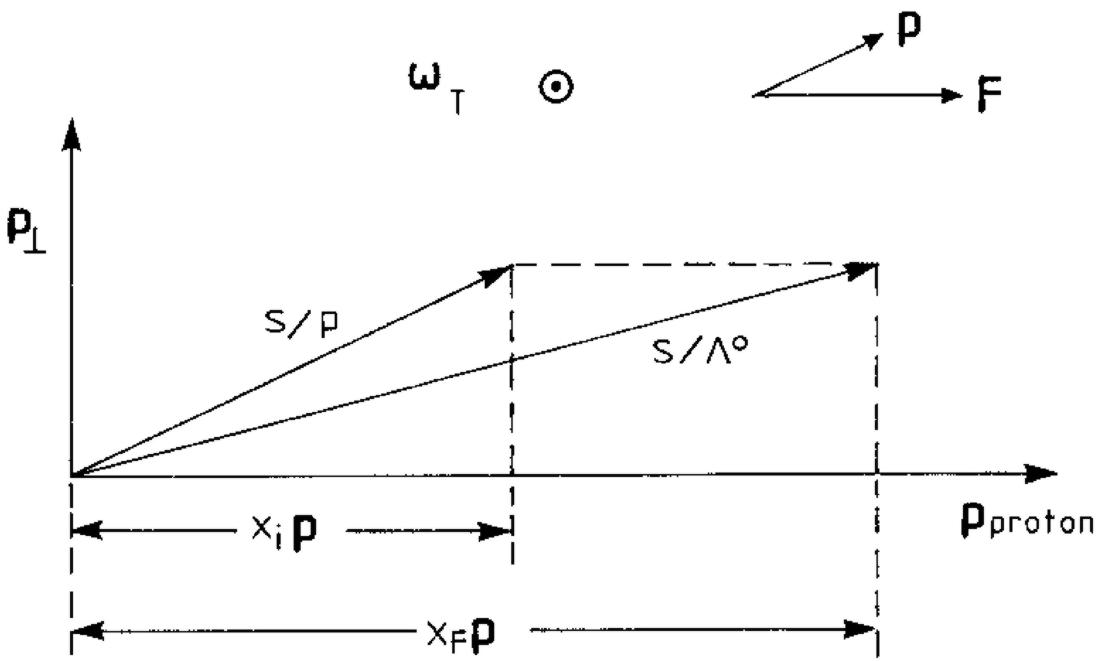


Comprehensive review of data by A.D. Panagiotou (Int.J.Mod.Phys.A 5 (1990) 1197)

Theoretical considerations

Perturbative QCD conserves helicity, which leads to $P_\Lambda \sim \alpha_s m_q/\sqrt{\hat{s}}$ (= small)
Kane, Pumplin & Repko, PRL 41 (1978) 1689

Many QCD-inspired models have been proposed, mostly based on
recombination of a ud diquark from the proton and an s quark from the sea
Spin-orbit coupling creates the polarization



The DeGrand-Miettinen model
PRD 23 (1981) 1227 & 24 (1981) 2419

Theoretical considerations

A comprehensive review of models by J. Felix (Mod.Phys.Lett.A 14 (1999) 827-842)
"In general, all models fail in fitting well the available experimental data on Λ polarization"

Most models give qualitative descriptions of the data for $p_T \lesssim 1 - 2\,\mathrm{GeV}/c$

However, for larger p_T, the recombination picture should become less adequate

How to explain that the large asymmetry persists at least to $p_T \approx 4$ GeV$/c$?

For large p_T perturbative QCD and collinear factorization should apply

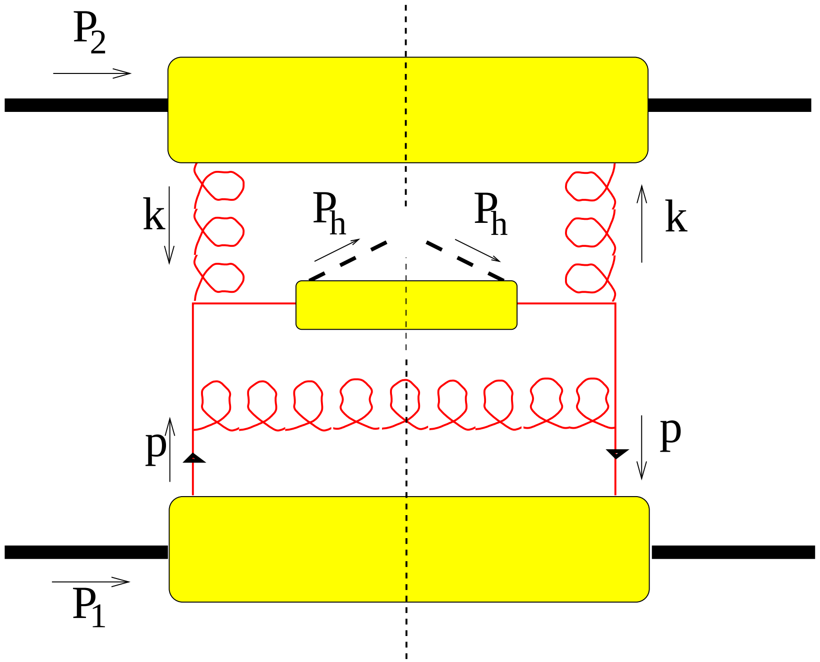
Collinear factorization

Consider for example the $qg \to qg$ subprocess

$$\sigma \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg\to qg} \otimes D_{\Lambda/q}(z)$$

$$\begin{aligned} q(x_1) &= \text{quark density} \\ g(x_2) &= \text{gluon density} \\ D_{\Lambda/q}(z) &= \Lambda \text{ fragmentation function} \end{aligned}$$

$$P_\Lambda \sim q(x_1) \otimes g(x_2) \otimes \hat{\sigma}_{qg\to qg} \otimes ?$$

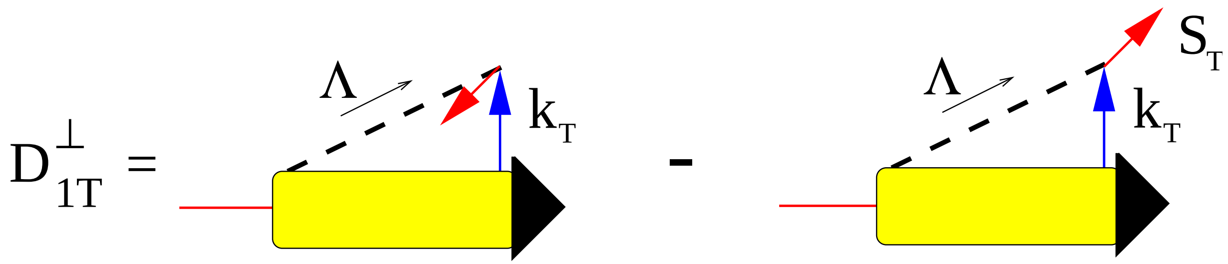


No leading twist collinear fragmentation function exists for $q \to \Lambda^\uparrow X$
(due to symmetry reasons)

Would be necessarily higher twist, which leads to a fall-off as $1/p_T$

Noncollinear factorization

Dropping the requirement of *collinear* factorization, does allow for a solution



Mulders & Tangerman, NPB 461 (1996) 197

- Transverse momentum dependent: $D_{1T}^{\perp}(z, \boldsymbol{k}_T)$
- A nonperturbative $\boldsymbol{k}_T \times \boldsymbol{S}_T$ dependence in the fragmentation process
- Allowed by the symmetries (parity and time reversal)

Λ polarization arises in the fragmentation of an *unpolarized* quark

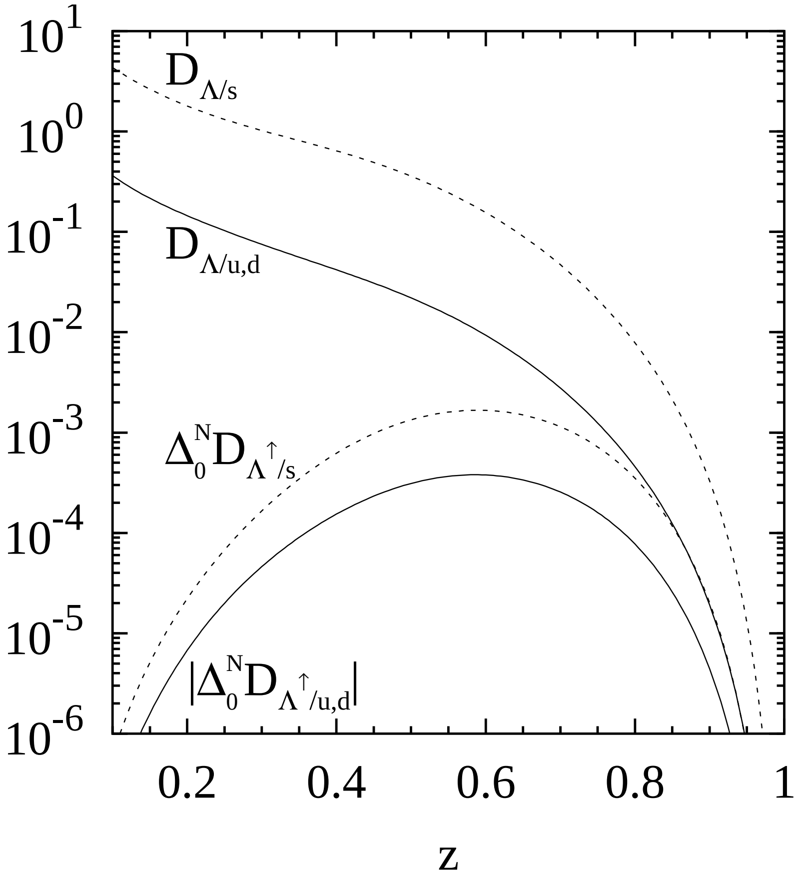
Hence, the suggested name "polarizing fragmentation function"

Extraction of $D_{1T}^{\perp}$

Fit to $p\,p(Be) \to \Lambda^{\uparrow}(\bar{\Lambda}^{\uparrow})\,X$ data with $p_T > 1$ GeV$/c$ to exclude the soft regime

M. Anselmino, D.B., U. D'Alesio, F. Murgia, PRD 63 (2001) 054029

Whether p_T cut is sufficient to ensure validity of the description is a matter of concern



Nevertheless, reasonable functions are obtained

$D_{\Lambda/q}$ = unpolarized fragmentation function

Indumathi *et al.*, PRD 58 (1998) 094014

$$\Delta_0^N D_{\Lambda^{\uparrow}/q} \sim \langle k_\perp \rangle \; D_{1T}^{\perp}(z, \langle k_\perp \rangle) \quad [\#\ \text{densities}]$$

$$z = P_\Lambda / p_q$$

High energy hadron collider data?

Validity of factorized description depends on a proper cross section description
This requires data at higher energies and higher p_T

Except for ISR, all data is from fixed target experiments, with $\sqrt{s} \lesssim 60$ GeV, requiring large K factors

Why no $\Lambda^\uparrow$ data from high energy hadron colliders, such as RHIC or Tevatron?

Capabilities to measure Λ polarization via $\Lambda \to p\,\pi^-$ are usually restricted to the midrapidity region, where the degree of transverse polarization is very small

$P_\Lambda = 0$ at $\eta = 0$ in $p\,p$ collisions in cms

Alternative: consider jet$+\Lambda$ production: $p\,p \to \left(\Lambda^\uparrow \text{jet}\right)$ jet X
Such an asymmetry does not need to vanish at $\eta = 0$

D.B., Bomhof, Hwang, Mulders, PLB 659 (2008) 127; D.B., arXiv:0907.1610

Jet+Λ production

The process $p\,p \to (\Lambda^{\uparrow}\text{jet})$ jet X can be studied at RHIC and LHC

For instance, ALICE can measure Λ's over a wide p_T range,

in a typical yearly run at least up to 16 GeV$/c$

Rapidity coverage of ALICE: $-0.9 \leq \eta \leq +0.9$

For jet rapidities in this kinematic region, the cross section is dominated by gluon-gluon ($gg{\to}gg$) scattering, *if* gluons fragmenting into Λ's are as important as quarks

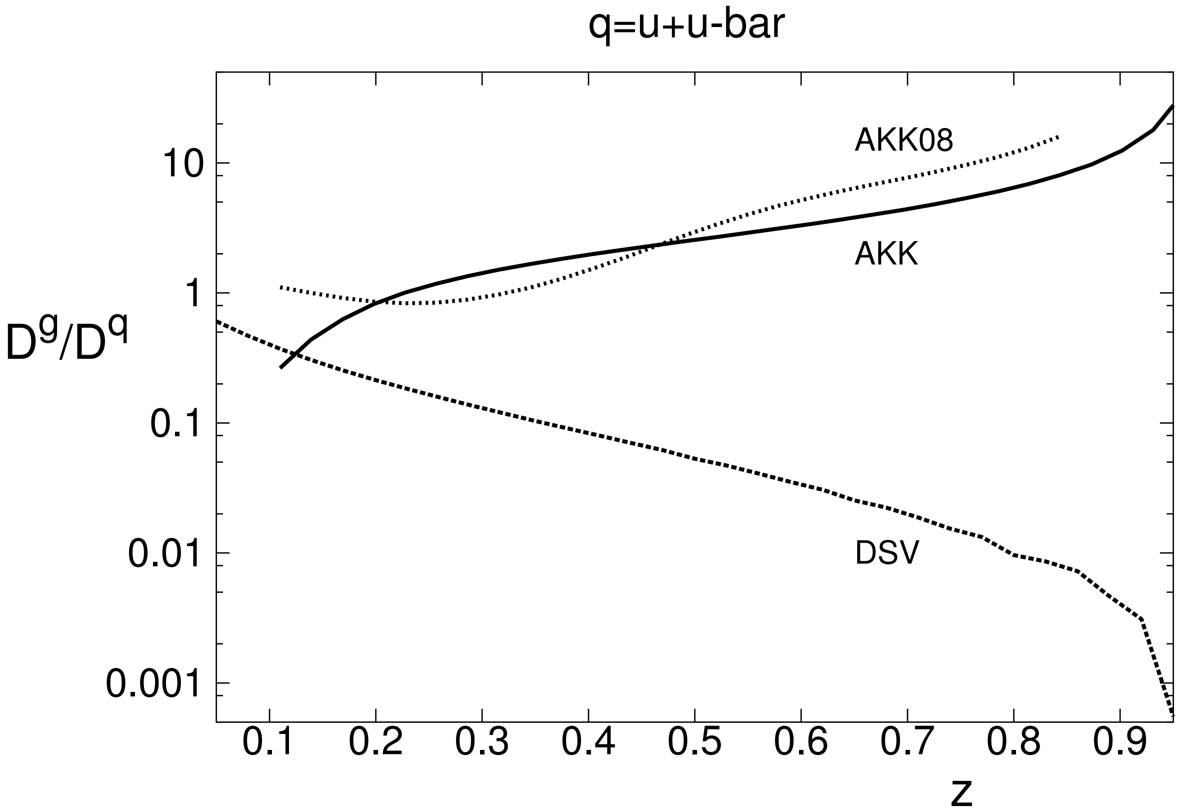
No model or fit for $D_{1T}^{\perp\,g}$ is available yet, so no predictions can be made in this case

Fit of $D_{1T}^{\perp}$ to $p\,p \to \Lambda^{\uparrow}\,X$ data not sensitive to $g \to \Lambda\,X$

The role of gluons in *unpolarized* Λ production even unclear

Fits of D_1 to only $e^+e^- \to \Lambda\,X$ data also not sensitive to $g \to \Lambda\,X$

Role of $g \to \Lambda X$



$Q = 10$ GeV

$q = u + \bar{u}$

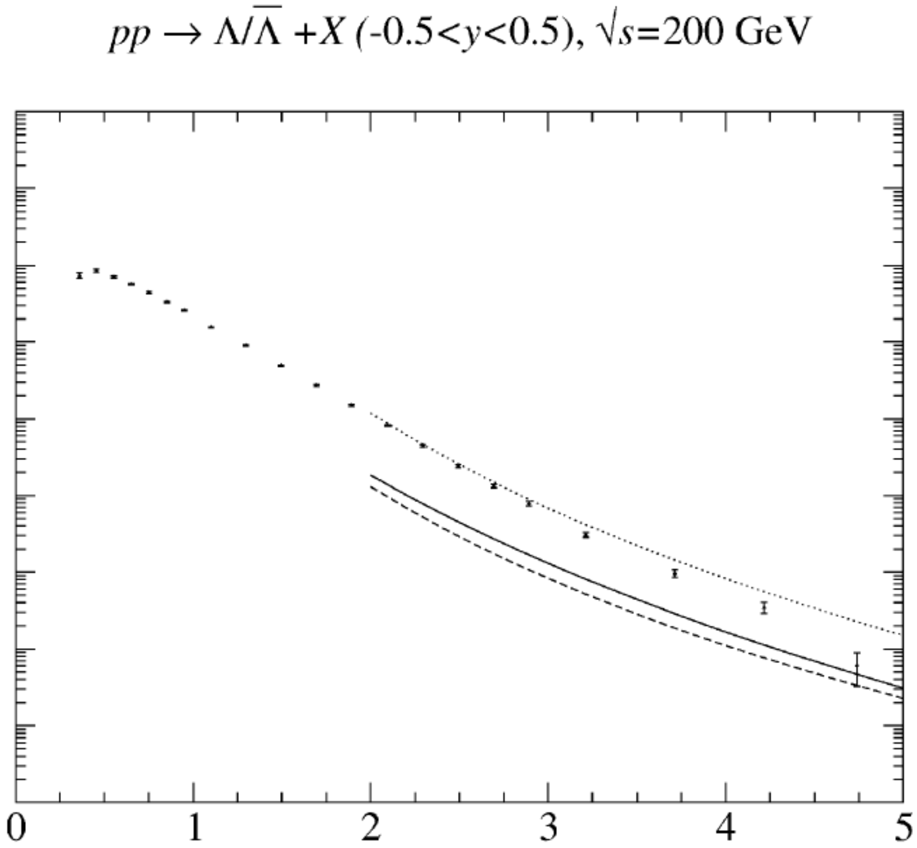
De Florian, Stratmann, Vogelsang [DSV] (PRD 57 (1998) 5811) (e^+e^- data only)

Albino, Kniehl, Kramer [AKK] (NPB 734 (2006) 50)

AKK update [AKK08] (NPB 803 (2008) 42)

Λ fragmentation function problem

Should we use the latest AKK08 then? Also problematic:



p_T distribution

solid: AKK08

dotted: AKK

dashed: DSV

data: STAR

"a possible inconsistency between the pp and e^+e^- reaction data for $\Lambda/\bar{\Lambda}$ production"

AKK, NPB 803 (2008) 42

Forward $p\,A \to \Lambda^{\uparrow}\,X$

Polarization of forward Λ's

Λ polarization is especially interesting in $p\,A$ reactions at very high $\sqrt{s}$, large A and η

In this kinematic regime of small x, saturation of the gluon density is expected

Larger z region probed, hence using valence quark polarizing fragmentation functions should be fine

The saturation scale Q_s and even its evolution with x could be probed in this way

D.B. & Dumitru, PLB 556 (2003) 33; D.B., Utermann, Wessels, PLB 671 (2009) 91

Could offer a direct probe of gluon saturation in both $p\,p$ and $p\,Pb$ collisions at LHC

Forward rapidity data

None of the existing data is in the saturation regime

In the forward direction often protons cannot be identified, which hampers the measurement of Λ polarization

Forward Λ's $(y = 2.75)$ in $d\,Au$ collisions have been identified via event topology

Abelev *et al.*, STAR Collaboration, PRC 76 (2007) 064904

Suggestion:

Use neutral decays $\Lambda \to n\,\pi^0$ (B.R. $\frac{1}{3}$) to measure Λ polarization at forward rapidities

Cork *et al.*, PR 120 (1960) 1000; Olsen *et al.*, PRL 24 (1970) 843

Hadron production in the saturation regime

The cross section of forward hadron production in the (near-)saturation regime:

pdf $\otimes$ dipole cross section $\otimes$ FF

Dumitru, Jalilian-Marian, PRL 89 (2002) 022301

Since $D_{1T}^{\perp}$ is $\boldsymbol{k}_T$-odd, it essentially probes the derivative of the dipole cross section

At transverse momenta of $\mathcal{O}(Q_s)$ the dipole cross section changes much

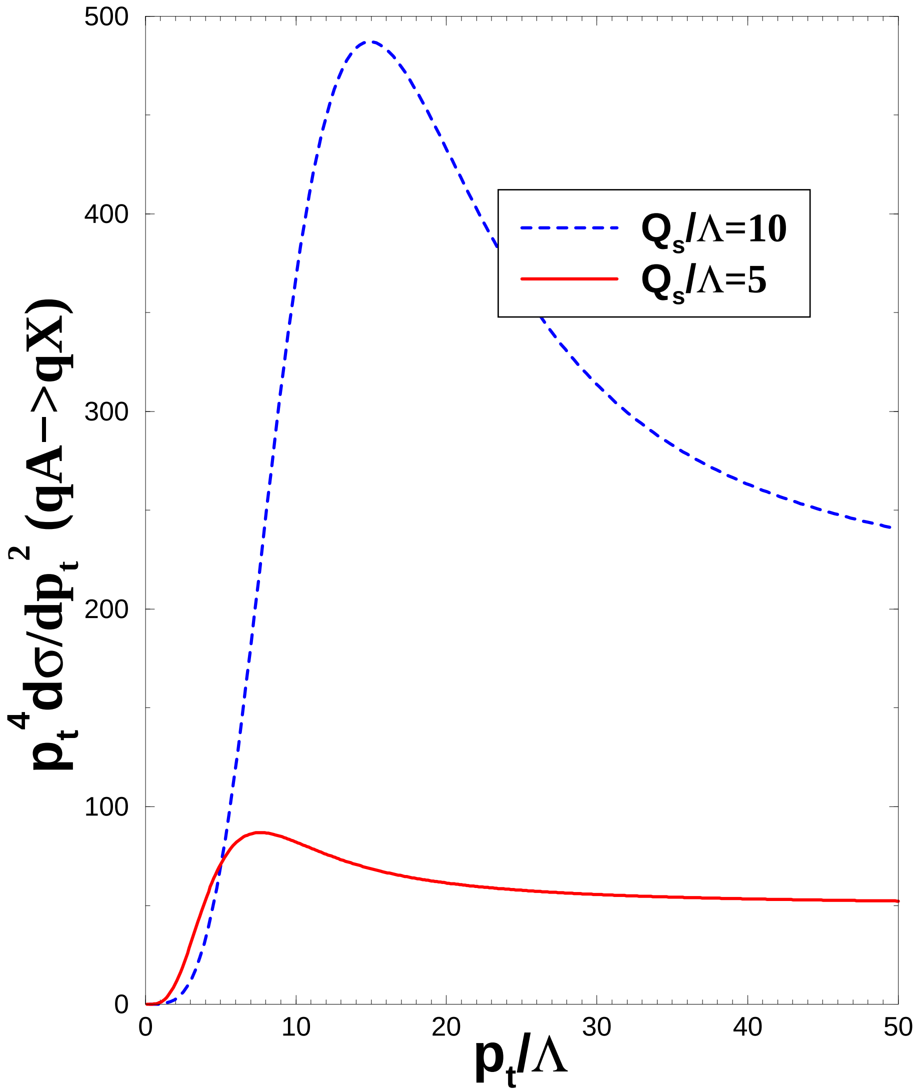
This leads to a Q_s-dependent peak in the Λ polarization

First demonstrated for the McLerran-Venugopalan model, which has constant Q_s

D.B. & Dumitru, PLB 556 (2003) 33

For an x-dependent Q_s a range of Q_s values is probed, so $a\ priori$ not clear whether this signature remains

Saturation effects in $p + A \to \Lambda + X$



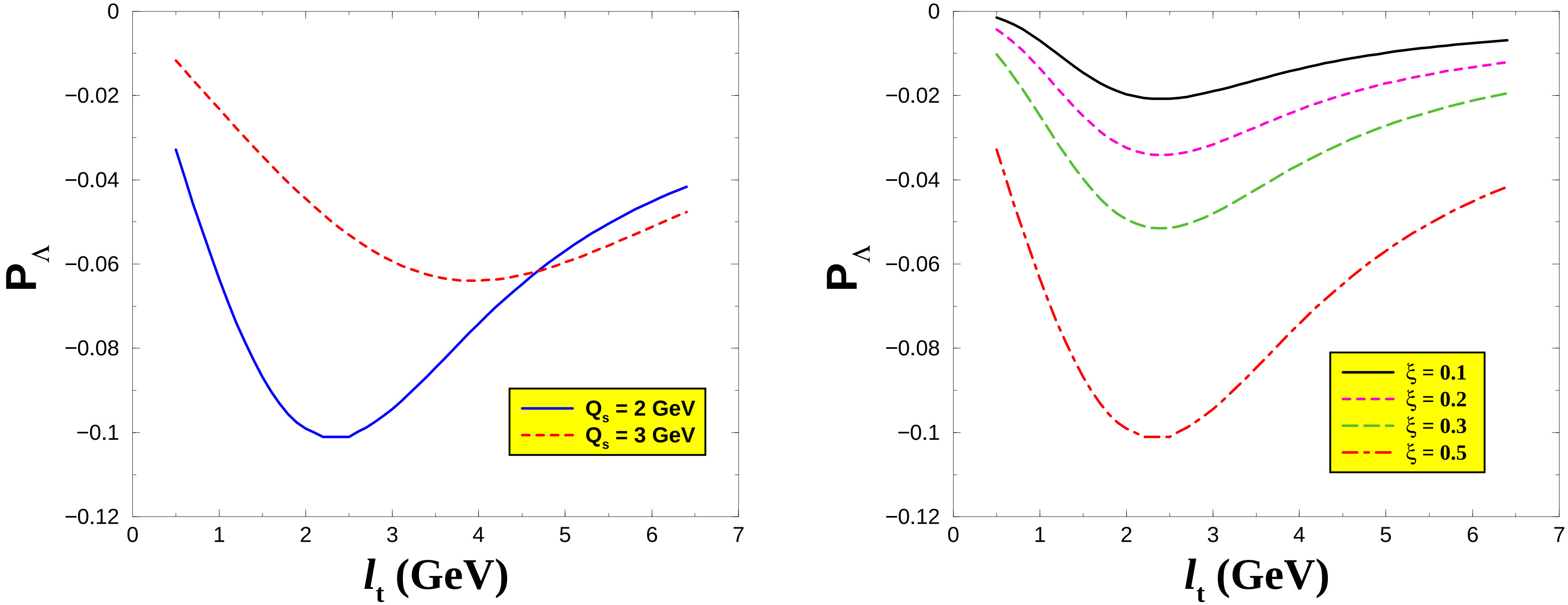
Partonic cross section in the MV model

At high p_T, leading twist pQCD predicts:

$$\frac{d\sigma(q\,A \to q\,X)}{d\boldsymbol{p}_T^2} \sim \frac{1}{\boldsymbol{p}_T^4}$$

For $p_T \lesssim Q_s$ saturation effects modify the cross section

Λ polarization in $p + A \to \Lambda^{\uparrow} + X$



D.B. & Dumitru, PLB 556 (2003) 33

In the MV model, where Q_s is a constant, the peak is $x_F (= \xi)$ independent

Phenomenological models

The saturation scale actually changes with the small-x values probed:

$$Q_s^2(x) \propto \left(\frac{1}{x}\right)^{\lambda}$$

Models that incorporate this are for instance:

- GBW model, describes well small-x DIS data

  Golec-Biernat, Wüsthoff, PRD 59 (1999) 014017

- DHJ model, describes well forward $d\,Au \to \pi X$ RHIC data

  Dumitru, Hayashigaki, Jalilian-Marian, NPA 765 (2006) 464

- GS model, describes well $d\,Au \to \pi X$ and DIS small-x data

  D.B., Utermann, Wessels, PRD 77 (2008) 054014

Dipole scattering amplitude

The dipole scattering amplitude of these phenomenological models:

$$N(q_t, x) \equiv \int d^2 r_t \, e^{i\vec{q}_t \cdot \vec{r}_t} \exp\left[-\frac{1}{4}\left(r_t^2 Q_s^2(x)\right)^{\gamma(q_t,x)}\right]$$

GBW model: $\gamma_{\mathrm{GBW}} = 1$

It leads to geometric scaling: $N = N(q_T^2/Q_s^2(x))$

In DIS ($q_t = Q$) geometric scaling of the cross section was observed for $x < 0.01$

Stasto, Golec-Biernat, Kwiecinski, PRL 86 (2001) 596

The saturation scale of the GBW model extracted from those DIS data:

$$Q_s(x) = 1\,\mathrm{GeV}\left(\frac{x_0}{x}\right)^{\lambda/2}$$

with $x_0 \simeq 3 \times 10^{-4}$ and $\lambda \simeq 0.3$

Geometric scaling at RHIC?

The DHJ model incorporates BFKL-type geometric scaling violations

$$\gamma_{\rm DHJ}(q_t, x) = \gamma_s + (1-\gamma_s)\,\frac{\log w}{\lambda y + d\sqrt{y} + \log w}$$

where $w = q_t^2/Q_s^2(x)$, $\gamma_s = 0.6275$, $d = 1.2$ and $y = \log 1/x$

The geometric scaling model rises more quickly towards 1 as $q_t \to \infty$

$$\gamma_{\rm GS}(w) = \gamma_s + (1-\gamma_s)\frac{(w^a-1)}{b+(w^a-1)}$$

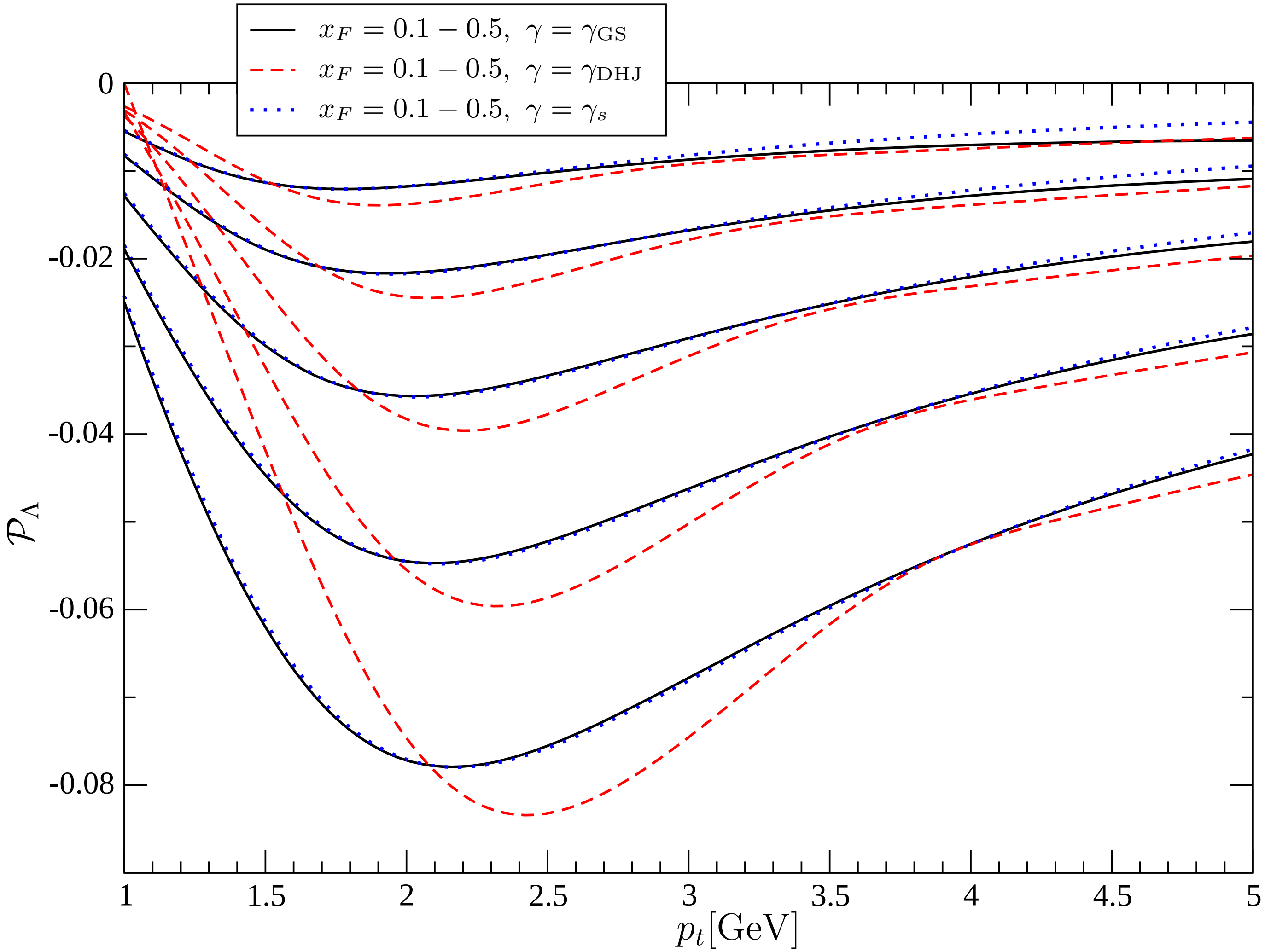
Here, $a = 2.82$ and $b = 168$ were fitted to the $d\,Au$ RHIC data

Both models describe well the forward pion production p_T spectra

DHJ and GS models lead to same conclusion about peak of Λ polarization:

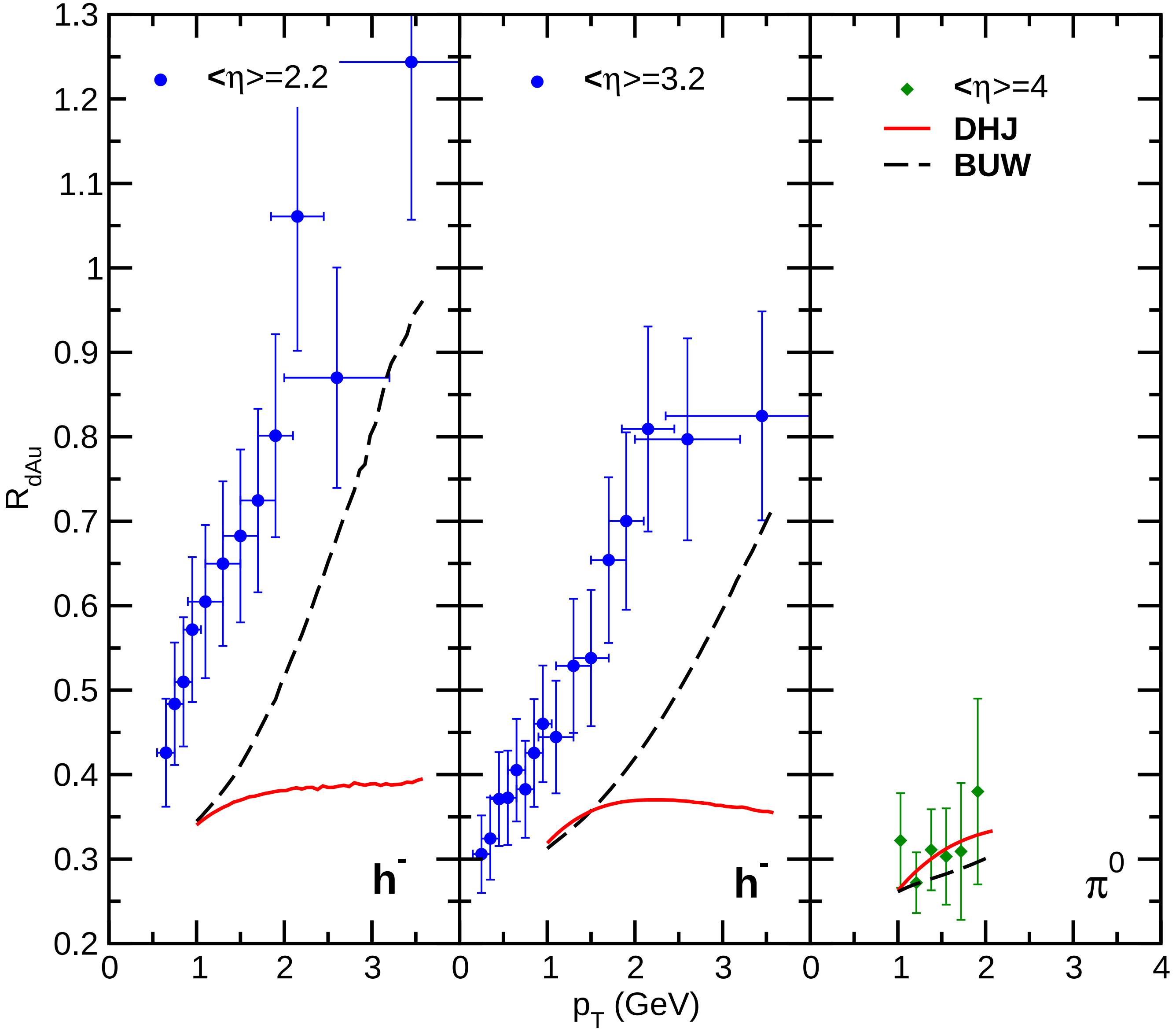
Its x_F dependence is to very good approximation the x dependence of Q_s!

Λ polarization in $p + Pb \to \Lambda^{\uparrow} + X$ at $\sqrt{s} = 8.8$ TeV



D.B., Utermann, Wessels, PLB 671 (2009) 91

R-ratio [Betemps, Goncalves, JHEP 0809 ('08) 019]



Conclusions

- At medium to high p_T, $p\,p \to \Lambda\,X$ may be described using $D_{1T}^{\perp}$
- Future jet+Λ production data hopefully will allow more solid extraction

  This can also clarify the role of gluons

  It can also shed light on the inconsistency between $p\,p$ and e^+e^- data
- The k_T-odd nature of $D_{1T}^{\perp}$ can be of use to small-x physics
- x_F dependence of the peak of Λ polarization directly probes the x dependence of Q_s
- In principle possible at LHC (at RHIC the peak is likely at too low p_T)
- Λ polarization studies at colliders could prove very interesting!